1. Introduction

Despite all improvements in vehicle crashworthiness, official information shows that the total number of road fatalities in the EU countries is more than 41000 each year. The lowest and highest values are corresponded to Malta and Latvia, 4 and 22 per 100000 inhabitants, respectively. Denmark has the lowest non-fatal road accidents and the highest value is in the Slovenia [107]. The information also indicates that from different types of road users, about 45% of the fatal accidents are caused by the vehicles; see Figure 1.1 [48].

Generally, for the purpose of vehicle body design, safety experts classify vehicle collisions as frontal, side, rear and rollover crashes. Based on the statistical investigations, the frontal impact followed by side impact are the two most frequent causes for fatalities [76]; see Figure 1.2 left. In the frontal impact, the vehicle frontal structure should absorb most of the crash energy by plastic deformation and prevent intrusion into the occupant compartment, especially in the case of offset crashes and collisions with narrow objects such as trees. Figure 1.2 right shows the probabilities of impact directions in the frontal collisions. Here, it can be seen that the collisions angle α is mostly less than 15 degree.

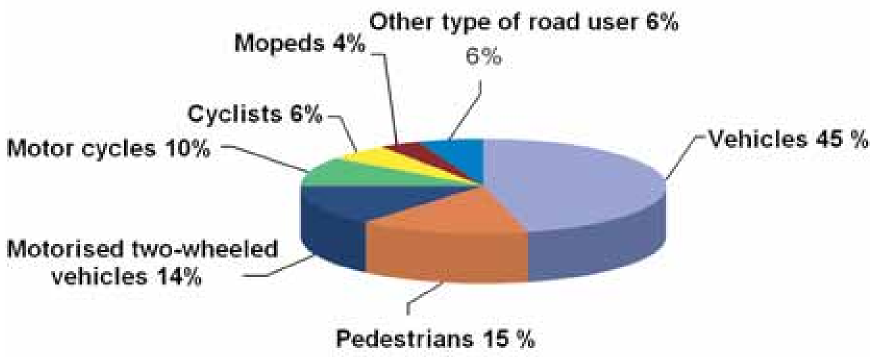
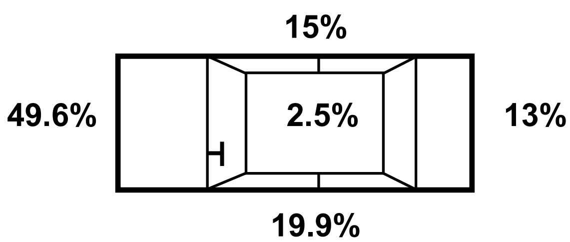


Figure 1.1: Percentage of accidents by different types of road users



$0° < \alpha < 15°$	64%
$15° < \alpha < 45°$	32%
$45° < \alpha < 90°$	4%

Figure 1.2: Probability of the different accidents scenarios (left), percentage of the impact angle in the case of frontal collisions (right)

The four parameters; traveling needs, quality of vehicles and roads, trauma care and finally human behavior can influence the traffic safety. Despite the fact that the four mentioned parameters are important, but special efforts have been done to improve the quality of vehicles and roads in the last decades. There are two fundamentally different approaches for safety evaluation of the vehicles. The first one uses the accident statistics to determine the occupant protection capacity. A vehicle type related data base which links injuries to the crash specifications indicates weak spots in a design. Since several years are needed to collect a representative amount of accident data, design improvements can only be applied to the later vehicle versions. To overcome this problem, a new approach namely predictive design is used. This method is based on accident standard tests under well defined circumstances. The collision tests spectrums are representative for the real situation on the road. Also it should consider several parameters like: the occupant's biomechanics, the impact location, speed and direction and the crash opponent.

Assessment of vehicle structural crashworthiness performance is originated in the United States of America before World War II. During the 1950's similar investigations started in Europe. The ultimate goal of these researches in both the USA and Europe was, to develop a test procedure that ensures occupant's safety in their own vehicles as well as those in partner vehicles in the event of a collision. These, however, should not ignore the significant number of real life collisions involving single vehicles striking objects such as trees, bridge abutments, roadside structures and buildings.

Today, as a result of more than 50 years investigations for vehicle's safety, several government mandated safety requirements must be fulfilled for different collision scenarios by the vehicles before coming to the market. Safety engineers must run barrier test to ensure vehicle structural integrity and compliance with regulations. In a typical full scale barrier test, a guided vehicle is driven into a barrier at a predetermined initial velocity. For example, based on the United States Federal Motors Vehicle Safety Standard FMVSS 208 a fully instrumented vehicle with numerous load cells, accelerometers and instrumented dummy (or dummies) in the driver (and passenger) seat(s) must impact a rigid barrier at zero degrees, as well as plus 30 degrees and minus 30 degrees, respectively, from an initial velocity of 48.2 km/h (30 mph). Several load cells in the barrier face monitor the impact data history. The unrestrained dummies in the driver and right front passenger must score injury assessment values below those established for human injury thresholds for the head, chest, and legs, for compliance with FMVSS 208. In 1979, the USA National Highway Traffic Safety Administration NHTSA started the New Car Assessment Program NCAP, where cars are tested in frontal impact at the higher impact speed of 56.3 km/h (35 mph). Much later, an NCAP program was started in Australia and one was being developed for Japan. In this test procedure, in addition to the supplemental restraint air bag, the dummy has to be restrained by three-point lap/shoulder belt system. These test procedures which include vehicle impact into a rigid barrier provide a method to assess the effectiveness of the restraint system, as it typically subjects the structure to high deceleration loads.

The European New Car Assessment Program Euro-NCAP is established in 1997 and now backed by five European Governments, the European Commission and motoring and consumer organizations in every EU country. In Germany the German motor club, (Allgemeiner Deutscher Automobil-Club, ADAC) supports this procedure. Based on this test program, the vehicle is impacted on deformable barrier with 40% overlap and velocity of 64 km/h (40 mph). Frontal offset impact with 40 to 50 percent overlap procedure is another type of testing which evaluates the structural integrity of the vehicle in the frontal offset impact condition. The impact target may be rigid or deformable. More deformations and intrusion and relatively less severe deceleration than full frontal impact are seen in this type of tests.

The FMVSS 208 is most effective in preventing head, femur and chest injuries and fatalities. However, it does not directly address lower limb and neck injuries and it does not produce the vehicle intrusion observed in many real life crashes. The EU directive 96/79 EC introduces frontal impact test requirements, including biomechanical criteria, to ensure a high level of protection in the event of a frontal impact. This Directive has additional test dummy injury response criteria, namely, head performance, neck injury, neck bending moment, thorax compression, femur force, tibia compression and movement of sliding knee joints. A fully equipped vehicle with hybrid III dummies which are installed in the each seats, is impacted on a deformable barrier with the velocity of 56.3 km/h (35 mph) and 40% overlap. The orientation of the barrier is such that the first contact of the vehicle with the barrier is on the steering-column side, where there is a choice between carrying out the test with a right-hand or left-hand drive vehicle.

There are similar full-scale tests for side impact. Based on the FMVSS 214 a deformable barrier of a particular mass and stiffness is thrust into the left or right side of the vehicle from some initial speed and certain angle. In this test, side impact dummies (“SID” for the USA and “EURO SID1” for Europe) are used in the driver and outboard rear seat locations. In order to assess the integrity of the fuel tank, the full-scale tests are conducted on the vehicle rear structure either by a deformable barrier or by a bullet car. To evaluate roof strength according to FMVSS 216, engineers apply a quasi-static load on the “greenhouse” and ensure that the roof deformation falls below a certain level for the applied load. A general summary of the current test requirements in the USA is given in Table 1.1 and for the European Union in Table 1.2. Also additional more severely requirements of the USA National Highway Traffic Safety Administration NHTSA’s and New Car Assessment Program NCAP are mentioned.

Increasing vehicle use contributes to air pollution that endangers public health. The reduction of the vehicle weight will improve the vehicle fuel efficiency. Vehicle designers achieve safety and fuel economy advances through using lightweight materials like aluminum, high strength steels, tailored beams and composite materials in the vehicle structures. It is obvious that the vehicle weight reduction must not menace vehicle safety. Normally crashworthiness optimization methods are used more and more in the design phase of the vehicles and even to redesign the vehicle's structures that already are in the market. The crashworthiness optimization procedure helps the vehicle designers to produce great performing vehicles or to redesign some parts of existing vehicles with outstanding fuel economy, while still maintaining the highest possible safety standards.

Table 1.1: Frontal crash test requirement in the USA

Requirement	FMVSS 208
Impact speed	48 km/h (NCAP 56 km/h)
Impact object (obstacle)	Fixed rigid barrier
Vehicle place and directions	Full frontal perpendicular and (not for NCAP) angles of +/- 30 degrees
Dummy type and conditions	Unrestrained and belt restrained (NCAP), 50th percentile Hybrid III adult male
Injury criteria	Head injury criterion 1000 Chest deceleration 60 g Chest deflection 50 mm Femur force 10000 N

Table 1.2: Frontal crash test requirement in the European Union

Requirement	74/297 EC	96/79 EC
Impact speed	50 km/h	56 km/h (Euro-NCAP 64 km/h)
Impact object (obstacle	Fixed rigid barrier	Fixed deformable barrier
Vehicle place and directions	Full frontal perpendicular	40% overlap of the vehicle width directly in line with barrier face
Dummy type and conditions	No dummies	Belt restrained (NCAP), 50th percentile Hybrid III adult male
Injury criteria or structural criteria	Steering wheel intrusion horizontal and vertical direction 127 mm	Head injury criterion 1000 Chest deceleration 60 g Chest deflection 50 mm Femur force 10000 N Additional criteria on chest (viscous), the neck, the knee, lower leg bending, foot/ankle compression and intrusion of the compartment

The goal of this research

In order to reduce design's time and cost, high efficient finite element software are used in the optimization process to find vehicles reaction in impacts with other vehicles or objects at varying speeds, conditions and locations including frontal, side, pole and rear impacts. Normally optimization procedures are used to design vehicle structure or redesign some parts of it for optimal performance across a variety of situations and reduce its weight.

Although today some success has been achieved in the crashworthiness improvement and fuel consumption reduction of the vehicles, but the number of road fatalities and global climate warming as a result of high CO_2 emission highlight the need for significant improvement in vehicle crashworthiness and fuel consumption reduction. This research leads to a design of low weight vehicle frontal crash elements, which absorb the highest energy and ensure deceleration levels which are tolerable for drivers and passengers. Therefore, the general goals of this study are as follows:

- To use a vehicle finite element model to find detail information about crush performance of vehicle frontal crash elements in a full frontal crash based on NCAP test procedures and specially to introduce the most effective vehicle's frontal crash elements.
- To use crashworthiness optimization procedure to reduce vehicle's weight in such a way that the vehicle's structure meets and exceeds safety standards without sacrificing affordability.
- To investigate experimentally and numerically the crush performance of some important vehicle's frontal crash elements like bumper beam and crash box and use multi design optimization *MDO* to find the optimum crash elements which absorb the most energy while have minimum weight.
- To investigate the crush performance of the low density materials like aluminum honeycomb and foam and to study experimentally and numerically the strengthening effects of them in the filled crash box and bumper beam.
- To use *MDO* procedure to optimize geometry and material properties of the filled crash box and bumper beam. The optimum crash box and bumper beam should have maximum specific energy absorption and absorb the same energy as optimum empty crash box and bumper beam.
- To review analytical formulations which predict the crush behavior of the empty and filled bumper beams and crash boxes. To use experimental crash data to calibrate these expressions. This calibrated formulation can be used in the primary stage of the vehicle's design.

- To investigate the crush performance of the empty and foam-filled composite crash boxes experimentally and numerically and to find optimum composite crash box. Finally to compare the optimum composite and aluminum crash boxes.

The second chapter of this study deals with the crashworthiness investigation of vehicles in a frontal impact. The crush performance of the vehicle's frontal crash elements is determined and the optimization procedure is used to minimize the weight of selected frontal crash elements while safety standards are met. In chapter three the crush behavior of the aluminum tubes which are used as crash box is investigated experimentally and numerically. The existing analytical expressions which describe the crush performance of the metallic tubes are summarized and calibrated. The multi objective optimization procedure is used to maximize the energy absorption and specific energy absorption of the aluminum crash boxes. The strengthening effect of aluminum honeycomb and foam in the filled crash box is determined experimentally and numerically in chapter four. An optimization procedure is used to maximize the specific energy absorption of the foam-filled crash box while it absorbs the same energy as optimum empty crash box. The analytical formulas to describe the crush performance of the filled crash boxes are presented and calibrated. The bending behavior of the aluminum empty and foam-filled beams which are used as vehicle bumper beams are investigated experimentally and numerically in chapter five. The analytical methods which are developed to determine the crush performance of empty and filled beams are reviewed and calibrated. Similar to aluminum crash box, optimization procedure is used to optimize the crush behavior of empty and foam-filled aluminum beams.

Finally the crush responses of empty and foam-filled composite crash boxes are determined experimentally and numerically in chapter six. As well as aluminum crash boxes, the optimization procedure is used to find optimum composite crash box. The crush performance of optimum composite crash box is compared with optimum aluminum one.